Summary of Research

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DATA ASSIMILATION AND TRANSPORT MODELING IN TERRESTRIAL AND PLANETARY ATMOSPHERES

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Data Assimilation and Transport Modeling in Terrestrial and Planetary Atmospheres

Data assimilation is a blanket term used to describe a number of techniques for retrieving important physical parameters from observational data, subject to constraints imposed by prior knowledge (such as, in the case of meteorology, the primitive equations that govern atmospheric motion). Since these newly developed methods make efficient use of computational resources, they are of great importance in the interpretation of the voluminous datasets that are now produced by satellite missions.

As proposed, these techniques have been applied to the study of the Martian and terrestrial atmospheres based on available satellite observations. In addition, a sophisticated hydrodynamic model (non-hydrostatic, and therefore applicable to the study of the interiors of the giant planets) has also been developed and successfully applied to the study of tidally induced motions in Jupiter.

Mars

For study of the huge meteorological dataset returned by the Mars Global Surveyor (MGS), a new baroclinic spectral general circulation model (GCM) has been utilized. It includes well-understood dynamics and the ability to be truncated to the resolution of the MGS observations [4]. Given the available observations for the mapping phase of the MGS mission, the model state is thus overdetermined by the observations [2]. Good agreement between the analyzed state and the Thermal Emission Spectrometer (TES) retrievals is obtained (rms error ~ 2K; 0 bias) [11]. The straightforward analysis also provides a satisfactory forecast (rms error < 4K) [12], but a future sequential assimilation will provide even better forecasts [14] and additional information about the sensitivities of the Martian atmospheric state (that should lead to improved future missions) [17]. It is now possible to assimilate the observed TES radiances directly [19], though some systematic differences between the individual TES retrievals and the assimilation analysis are evident [21]. A full year's analysis of TES-derived meteorology shows generally good agreement with traditional GCM calculations [22]: the average temperatures are generally warmer by about 10 K, the equator-pole temperature gradient and thus the mean zonal wind are consistent with model predictions (and with the gradient wind approximation). The meridional Hadley cell is about as predicted, but the transition from northern summer to southern summer circulation is extremely rapid. With the goal of validating this TES dataset against other meteorological measurements, a systematic comparison with radio occultation profiles has been conducted [24]. Relatively large rms errors (~ 6K) are an indication that the near-surface TES retrievals and the assimilation model ground temperature and boundary layer forward models should be revised considerably. In particular, low-level inversions that are common in the (nighttime) occultation profiles are not found in the analyses.

The assimilation of TES-derived water vapor column amounts awaits improved Martian atmospheric transport models. Current models are able to produce a closed water cycle that resembles Mars Atmospheric Water Detector (MAWD) and TES observations [5]. However, these models show very small diurnal variations of water vapor column [1] and this lack of variation cannot be verified from the limited TES observing pattern. Nevertheless, the model can be used to simulate near-surface ground water (which exists as adsorbed water, vapor, and ice). The computed amounts are smaller than what has generally been derived from models which ignore the seasonal variation of atmospheric column [3]. The Mars Odyssey (MO) promises to provide the observations that can verify the new predictions [16] of smaller near-surface water content in the southern hemisphere than in the northern hemisphere. (As of spring 2002, however, MO has not yet seen below the seasonal frost deposits in the northern hemisphere.)

Earth

Data assimilation of terrestrial aerosol observations from space is difficult because of the many variables associated with the size distribution. In an effort to simplify this process, a moment-oriented approach to the modeling of stratospheric aerosol sedimentation was developed. This showed that the timescale for evolution of volcanically injected sulfuric acid aerosol clouds in the stratosphere lengthens with time [6], consistent with observations of visible extinction by SAGE II and at infrared wavelengths by HALOE [7]. The predictions of power-law decay of extinction are borne out by the data [8]. This in turn allows the formulation of scaling laws that predict the integrated climatic impact of a volcanic eruption as a function of total eruptive mass [9]. A detailed study of the ratios of infrared to visible extinction, however, shows much less time variation than predicted [10], consistent with an effective radius of the post-Pinatubo volcanic aerosol much smaller than expected [15]. This has spurred the development of a full assimilation model for the study of satellite measurements of stratospheric aerosol [20]. The model analyzes the full range of the particle size distribution, the mean meridional Brewer-Dobson circulation in the stratosphere, and source and sink terms of sulfur dioxide on a monthly mean basis [23].

Jupiter

The innermost Galilean satellites of Jupiter all show interesting phenomena that can ultimately be traced to anomalously high heating rates: the volcanoes of Io; a probable liquid water layer in Europa; and an active magnetic dynamo in Ganymede. The ultimate source of this energy is tidal dissipation in Jupiter: Io raises a bulge on the fluid planet (analogous to the ocean tides raised by our moon) which exerts a torque back on Io, accelerating it in its orbital motion, leading to strong interactions with the other satellites. This torque is only possible if some (friction-like) dissipation mechanism delays the occurrence of the bulge until after the passage of the exciting satellite. No adequate source of this dissipation in Jupiter has yet been identified, largely because of the lack of a complete hydrodynamic model of this planet [13]. Such a model has now been developed and a number of previously troubling questions about

Jovian tidal dynamics have now been answered [18]. Among these are the correct boundary condition that connects the adiabatic envelope of the planet to its stably stratified atmosphere; the role of a stable layer in the envelope in amplifying tidal motions; the correct definition of the tidal dissipation factor (Q) in a compressible body; and the relation of the atmospheric wave flux to the tidal torque. Still under investigation is the question of where the angular momentum exchanged in the tidal interaction is deposited in the planet.

Papers, Reports, and Presentations (in chronological order)

[1] Houben, H., 1999. The Martian diurnal water cycle, *Adv. Spa. Res.* **23**, 1587-1590.

[2] Houben, H., 1999. Assimilation of Mars Global Surveyor meteorological data, *Adv. Spa. Res.* **23**, 1899-1902.

[3] Houben, H., 1999. Soil moisture predictions for Mars Polar Lander, 30th Lunar and Planetary Science Conference, Houston.

[4] Houben, H., 1999. A data assimilation model for the Martian atmosphere, 3rd WMO Symposium on Assimilation of Observations in Meteorology and Oceanography, Quebec.

[5] Houben, H., R. M. Haberle, M. M. Joshi, 1999. The Martian water cycle based on 3-d modeling, 5th International Conference on Mars, Pasadena.

[6] Houben, H., O. B. Toon, P. Hamill, R. W. Bergstrom, 1999. Are we reaching the stratospheric aerosol background level? SAGE II Science Team Meeting, Hampton, VA.

[7] Bergstrom, R. W., H. Houben, P. Hamill, 1999. Approaching the stratospheric aerosol background, UARS Science Team Meeting, Virginia Beach, VA.

[8] Hamill, P., H. Houben, R. W. Bergstrom, O. Kalashnikova, 1999. Are we now at a background stratospheric aerosol level? *EOS* **80**, Fall Meeting Supplement, F169.

[9] Houben, H., R. W. Bergstrom, O. B. Toon, R. E. Young, 1999. Climatic consequences of volcanic eruptions based on 3-d modeling. *EOS* **80**, Fall Meeting Supplement, F219.

[10] Houben, H., R. W. Bergstrom, and O. B. Toon, Global assimilation of satellite stratospheric aerosol data, *EOS* **81**, Spring Meeting Supplement, May 2000.

[11] Houben, H., Data assimilation of TES meteorology, MGS Workshop on Water and Atmospheric Physics, Boulder, CO, June 2000.

[12] Houben, H., Martian meteorology from the Mars Global Surveyor, Meteorology at the Millennium, 105, Cambridge, UK, July, 2000.

[13] Houben, H., and R. E. Young, Re-examination of tidal dissipation in Jupiter, COSPAR, Warsaw, Poland, July 2000.

[14] Houben, H., The Mars Global Surveyor as a platform for operational meteorology, *Bull. A. A. S.* **32**, 1096-1097, 2000.

[15] Houben, H., Modeling studies of the Mt. Pinatubo volcanic cloud in the stratosphere, Seminar at NASA/Ames Research Center, November, 2000.

[16] Houben, H., The current Martian water cycle based on 3-D modeling and consequences for near-surface water deposits, *EOS* **81**, Fall Meeting Supplement, December 2000.

[17] Houben, H., Operational meteorology for the Martian atmosphere, Gierasch 60th Birthday Symposium, Cornell U., Ithaca, NY, March 2001.

[18] Houben, H., R. E. Young, A. Showman, and I. Mosqueira, Full hydrodynamic calculations of tidal dissipation in Jupiter, Jupiter: Planet, Satellites & Magnetosphere, Boulder, CO, June 2001.

[19] Houben, H., and R. W. Bergstrom, Martian meteorology from the direct assimilation of TES radiances (Invited), 8th Science Assembly of the International Association of Meteorology and Atmospheric Sciences, Innsbruck, Austria, July 2001.

[20] Houben, H., and R. W. Bergstrom, UARS observations of the Mt. Pinatubo stratospheric cloud, UARS 10th Anniversary Science Meeting, Goddard Space Flight Center, Greenbelt, MD, September 2001.

[21] Houben, H., R. W. Bergstrom, and J. Hollingsworth, Martian meteorology from 4-D variational assimilation of TES radiances, *Bull. A. A. S.* **33**, 1073, 2001.

[22] Houben, H., and R. W. Bergstrom, Meteorology for the Mars Global Surveyor mapping year based on Thermal Emission Spectrometer data assimilation, *EOS Trans. AGU* **47**, Fall Meeting Supplement, Abstract P32E-08, 2001.

[23] Hamill, P., Houben, H., and R. W. Bergstrom, Satellite observations of the Mt. Pinatubo stratospheric cloud, *EOS Trans. AGU* **47**, Fall Meeting Supplement, Abstract U32A-0009, 2001.

[24] Houben, H., R. W. Bergstrom, and J. Hollingsworth, Data fusion of Mars Global Surveyor meteorological datasets, EGS02-A-04998, 27th General Assembly of the European Geophysical Society, Nice, France, April 2002.

APPENDIX

Subject Inventions Certification

There were no subject inventions required to be disclosed to NASA which resulted from this work. There were no subcontracts awarded under this Cooperative Agreement.